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BENEFITS OF MAGNETICALLY LEVITATED HIGH-SPEED TRANSPORTATION FOR THE UNITED STATES

REPORT

PREPARED BY THE

MAGLEV TECHNOLOGY ADVISORY COMMITTEE

REPORTING TO THE

COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS

UNITED STATES SENATE

AUGUST, 1989

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United States Senate
COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS
WASHINGTON, DC 20510-6175

August 1, 1989

Dear Mr. Chairman:

I commend to your attention a report prepared by the Maglev Technical Advisory Committee (MTAC) entitled The Benefits of Magnetically Levitated High-Speed Transportation for the United States, Volume 1 -- Executive Report.

The Advisory Committee that prepared this report is made up of scientists and engineers with expertise in transportation engineering and magnetics. The MTAC was convened at the request of the Chairman of the Subcommittee on Water Resources, Transportation and Infrastructure in October, 1988 to address some of the key questions concerning the future of maglev transportation on the interstate highway rights-of-way.

This report tells us that maglev is achievable: "High speed maglev systems can be built to run beside existing interstate highways at acceptable cost and without significantly interfering with normal highway operations." And, more importantly, that there are compelling reasons for the United States to pursue maglev: "Maglev is increasingly recognized as the next revolution in transportation."

On behalf of the myself and my colleagues on this Committee, I would like to thank all of the scientists and engineers that contributed to the report. Their work is valuable, and is appreciated.

Maglev was invented in the United States by these same American scientists, but so far is being built in Japan. There is time to turn this around. I hope there is the will.

Sincerely,

Daniel Patrick Moynihan

The Honorable Quentin N. Burdick
Committee on Environment and Public Works
United States Senate
Washington, DC 20510

FOREWORD

The genius of U.S. democracy is that about twice a decade it produces a new President. Policies can be reversed. Structures can be remade. The American blessing is to have invented a system that allows us to reimagine the world every four years.
— Charles Krauthammer, "The Secret of Our Success,"
Time, 30 January 1989

Technological revolutions occurring over the past few years have conjured renewed visions of the future across the spectrum of the American imagination. In 1986, the advent of the "warm" superconductor enabled a new set of feasible technologies to be revisited in fresher contexts—a list of options that includes a technology known as Maglev, for *magnetically levitated transportation*. Exploiting the levitating properties of superconductors for high speed vehicles is the topic of this report—a commercial application of superconductivity that, if implemented in America, could be the crucible within which we can measure America's competitive resolve as we enter the next century. But America must make critical decisions soon if we are to have any hope of ever reaping economic benefits from the domestic development and deployment of Maglev. And these decisions will be every bit as political as they are scientific or economic.

This report...challenges the best and the brightest in America to reassert technological leadership.

This report is intended to foster and expedite these decisions by detailing the technological and economic justification for America to pursue its own Maglev system. It is a culmination of dynamic and prescient leadership on the part of the United States Senate coupled with the expertise and resolve of a volunteer group of American scientists, academics, and Maglev experts. This report intentionally throws down the proverbial gauntlet to the American corporate, scientific, and government infrastructure—challenging the best and the brightest in America to begin to reassert technological leadership by undertaking a project of major proportions—the construction of a U.S. superconducting Maglev prototype in this country within the next four to five years.

Maglev is to diesel locomotives what Star Trek is to Wagon Train.

It has been asserted, tongue-in-cheek, that Maglev is to diesel locomotives what *Star Trek* is to *Wagon Train*. Why? Because Maglev is more than just moving people and cargo from point to point at rapid speeds. It is about tomorrow's technology. In essence, comparing what is essentially guided terrestrial flight (i.e., Maglev) to a steel-wheel train (i.e., Amtrak) is bordering on the illogical. But these are the facts: Maglev is a revolutionary concept that will one day—sooner than we think—be a reality. The question is whether it will be a reality rooted in American science that will first blossom abroad, or a technology that this nation can capture and savor as its own.

For Maglev is indeed an American concept. For many of the participants in this study, drafting this document brought on not only a sense of heightened excitement but also a sense of *deja vu*, because America pioneered the technology of levitated superconducting transportation in the 1960s and 1970s—but only to the prototype scale model stage. The effort was abandoned in 1975 for lack of federal funds but was picked up and carried on in a spirit of raging incrementalism by the Japanese. That America walked away from this effort more than a decade ago is demonstrative of the commercial technology lapses our country is prone to stumble into, characterized most visibly by the forfeiting of billion dollar markets in consumer electronics and dynamic random access memory

semiconductors—two American inventions commercially exploited by Japan. This study is intended to be both a blueprint and a road map for avoiding this scenario in Maglev and the enabling technologies for superconductors and cryogenic refrigerators.

The reality still remains, however, that an individual wishing to ride in a high-tech Maglev vehicle at speeds approaching 325 miles per hour must first book a flight to Japan—to Kyushu Island, where the Japanese full scale superconducting Maglev is being put through its paces. Whether or not, and how, America can leapfrog the Japanese technology, and how to fund that effort are core questions facing our industrial and political leaders today. Because of the overseas competition evolving in this technology, America's window of opportunity to re-entering the Maglev market is already beginning to close. As in most technological endeavors, there is no luxury of time.

But simply *knowing* our problems won't solve them. The careful reader of this study will recognize two key points: One, we have the capability and talent to surpass the Japanese in superconding Maglev technology; and two, that capability must be galvanized and activated by the unique American zeal that drove us to pioneer it in the first place—the zeal to win.

Maglev is an investment that could yield a "win-win" situation...American jobs, American manufacturing.

Recognition of the need for this type of zeal—to be competitive in high technology arenas—has lately permeated both public and corporate landscapes. This acknowledgment has been coupled with renewed concern over America's fossil-fuel appetite, greenhouse effect precursors, urban air quality problems, air traffic congestion, and motor-vehicle gridlock. While a U.S. commitment to Maglev is no instant panacea for these problems, it is an investment that could yield a "win-win" result for the United States: we can win in one sense by pursuing a technology that might mitigate some basic American transportation/environmental problems; and we would also win by proving to ourselves that we can approach the next millenium as innovators, builders, and creators willing to re-visit a technology invented on American soil, but this time exploited to the benefit of American jobs, American manufacturing, and the American economy. To make that commitment will require skilled leadership on the part of our Administration, Congress, our industrial base, the scientific and academic communities, and the American public.

It is high time to re-imagine and re-awaken America's technology prowess.

Which brings us back to the above citation by Mr. Charles Krauthammer. The authors of this report do in fact believe that it is time to reverse those 1970s policies that led to the premature scuttling of the American Maglev effort. We also believe it is time to secure the funding and cooperation that will lead to invention and U.S. preeminence in the Maglev field. But we also feel that it is high time to re-imagine and re-awaken America's technology prowess. And if that re-awakening takes the shape of a flagship U.S. Maglev project, it can serve as both a symbol as well as a visible, tangible measure of America's large-scale technological rebirth. It is our sincere belief and utmost hope that this report can help bring that victory home. It is a difficult task, but one that could yield dividends measured in spirit and pride that would go far beyond our imaginings, or even our re-imaginings. Time will tell—as long as we realize we don't have a lot of it.

PREFACE

At the request of Senator Daniel Patrick Moynihan, the Maglev Technology Advisory Committee (MTAC) was organized in October 1988 to examine the technical and economic feasibility of running Maglev transport systems along U.S. Interstate highway rights of way. The committee was also asked to assess the potential environmental, energy, social, and industrial benefits that would result from large scale implementation of Maglev in the United States.

MTAC members come from industry, universities, national laboratories, and government agencies. They have extensive experience in Maglev design and technology and the various disciplines related to it. Participation is on a voluntary and non-funded basis.

Results of the MTAC study are presented in two volumes. Volume 1, the Executive Report, summarizes the study; Volume 2, the Technical Report, presents detailed descriptions and analyses generated by the participants.

The study was organized and coordinated by Gordon Danby and James Powell. MTAC members and their affiliations are listed on the right.

The views expressed in this report are those of the authors, and do not necessarily represent the positions of their affiliated organizations.

Grumman Corporation published and distributed the report. Mr. Andrew Samet, legislative director for Senator Moynihan, provided invaluable assistance to the study, and MTAC members wish to express their appreciation and gratitude for his efforts as well as the many individuals who helped prepare this report: Annamarie Spira, Richard Tulipano, and Trudi Neuhoff at Brookhaven National Laboratory, who did extensive typing and illustration for the original manuscript, and the Grumman production team—Janet Williams, managing editor; Ted Kole, art director; and Jim Veccia, cover artist. Special acknowledgment is also due Karen Bright of Bright Design Inc. for creating the Maglev logo.

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SUMMARY OF KEY FINDINGS

The Maglev Technology Advisory Committee concludes that Maglev (magnetic levitation) technology offers uniquely attractive solutions for U.S. domestic and worldwide transportation needs and is destined to soon become a significant part of the transportation market. Construction of the next generation transportation system will be a massive, major industrial venture, and it is vital that the U.S. play a major role.

There is a narrow window of opportunity for the U.S. to rejoin the Maglev effort. If we act quickly, we can be a leader in this vitally important field. If we do not, the rewards will go to others. This program should have as its goal the construction and operation of two or more full scale Maglev demonstration tracks within four to five years. These demonstration tracks would use different design approaches. Selection of the best approach for commercial application would be made after two years of testing under realistic Interstate conditions.

In addition to developing and demonstrating second generation Maglev technology, it will be necessary to pass legislation—federal and state—to enable the use of Interstate rights of way for Maglev systems and to establish certification and safety standards.

The Committee strongly recommends that, for the reasons listed below, the U.S. institute a program to develop and demonstrate second generation Maglev technology suitable for application to the Interstate highway network.

1. The U.S. transportation system has severe problems. Both ground and air transport experience congestion and lengthy delays. Emissions cause unacceptable pollution at many locations. Our autos and airplanes depend on petroleum fuel, which will become scarcer and more expensive in the years ahead. Oil imports are a major factor in the U.S. trade deficit and raise serious concerns about energy security. Constraints on land, air quality, and fuel severely limit the ability of present modes of transport to deal with these problems. Maglev, an efficient, clean, high-speed form of transport, offers major improvements in passenger and cargo capabilities and can help solve our transport problems.
2. It is technically and economically feasible to build high speed Maglev systems along existing Interstate highways. Maglev construction and operation will not disrupt or degrade highway traffic. Guideways and roadways can be adequately separated for safety and security. Induced wind and noise effects at the roadway are small.
3. Maglev will greatly enhance U.S. mobility, relieving our congested highways and airports, without additional land requirements. A two-way Maglev system on an existing Interstate right of way can easily carry 100,000 passengers per day at speeds of 200 to 300 miles per hour, along with freight handling capability.
4. Maglev requires much less energy input than other transport modes. Per passenger mile, autos consume approximately two times as much primary thermal energy as Maglev; airplanes consume four times as much.
5. Maglev will improve U.S. energy security and trade balance by reducing oil imports. Maglev uses electricity generated by central station power plants—fueled by coal, nuclear, or hydro rather than petroleum.
6. Maglev will yield a much cleaner environment by greatly reducing pollutants from autos, trucks, and airplanes. Hydrocarbons, carbon monoxide, and tire particulate emissions are virtually eliminated, while nitrogen oxides and combustion particulates are greatly reduced. Maglev reduces carbon dioxide emissions—the principal contributor to global warming—by a factor of 2 over autos and a factor of 4 over airplanes.
7. Implementation of superconducting Maglev would provide a major push toward commercializing superconductivity for a wide range of applications.

including electric power generation, transmission, and storage; industrial processing; computers and electronics.

8. Ultimately, Maglev could save many billions of dollars per year because of its energy efficiency and high transport capacity. The U.S. now spends $600 billion per year on transportation. In the next 20 years we will spend at least $12,000 billion at present rates. In fact, we will spend much more, since demand and the real cost of fuels will increase.

9. Major U.S. economic and population centers can be connected by Maglev networks located along the Interstates. Travel will be very fast—much faster than highway and comparable to delay-free airplanes—low cost, and virtually unlimited in capacity.

10. Maglev integrates readily with present air, auto, and rail transport modes. Airline passengers could board Maglev vehicles at airports, for example, continuing on to their destinations.

11. Three types of Maglev systems appear practical: metropolitan area feeders, which connect urban and suburban regions; linear corridors, which tie two or more cities together; and multistate networks, which connect major centers in broad areas of the U.S.

12. Maglev will start to become an important industry by the year 2000—only 11 years away—and a major mode of transport in the next century. To compete in this arena, the United States must start industrial development of Maglev very quickly. If not, Maglev production and sales—billions of dollars annually—will be foreign dominated. A substantial portion of Maglev components will be manufactured outside the U.S., and the profits will go offshore.

13. Japanese and German first-generation Maglev systems have operated successfully at high speed with full scale vehicles. Commercial systems based on this technology are planned abroad and are being considered for the U.S. Low speed "people mover" systems are in use at a number of locations. What the U.S. needs is development of second-generation, high speed Maglev systems that can be installed along the Interstates at acceptable cost, with minimal reconstruction of existing structures and little or no disruption in highway traffic.

14. We favor the superconducting Maglev approach because of its potential for lightweight, low cost guideways. Moreover, superconducting Maglev achieves a much larger clearance between vehicle and guideway—6 inches compared to 3/8 inch for electromagnetic Maglev—which results in greater tolerances and less expensive construction. Finally, the propulsion system for superconducting Maglev has considerably longer pitch and is therefore simpler to construct.

15. Present low temperature superconducting magnets and cryogenic refrigerators are technically and economically practical for superconducting Maglev. There is much experience with this technology, including commercial applications, and the systems are very reliable and cost effective. Superconducting magnets are only a small portion of Maglev vehicle cost, which in turn is small compared to guideway cost. Superconducting Maglev does not need to wait for high temperature superconductors to be practical. However, Maglev could be one of the first markets for high-temperature superconductors when they become available.

16. Capital investment for commercial Maglev systems can come from both public and private sources. Returns from real estate development near stations are expected to be an important source of Maglev revenue. Capture of these potential real estate returns through grants of development rights can be a powerful incentive to private investors. In general, mature Maglev systems should yield enough revenue—from passengers, freight, and real estate development—to cover debt service and operating costs. Long-term government subsidies will therefore not be needed.

WHAT IS MAGLEV?

Maglev is the suspension, guidance, and propulsion of a vehicle by magnetic forces, with no physical contact between the vehicle and its guideway. Maglev allows much greater speeds than wheeled suspensions and virtually eliminates roadbed maintenance.

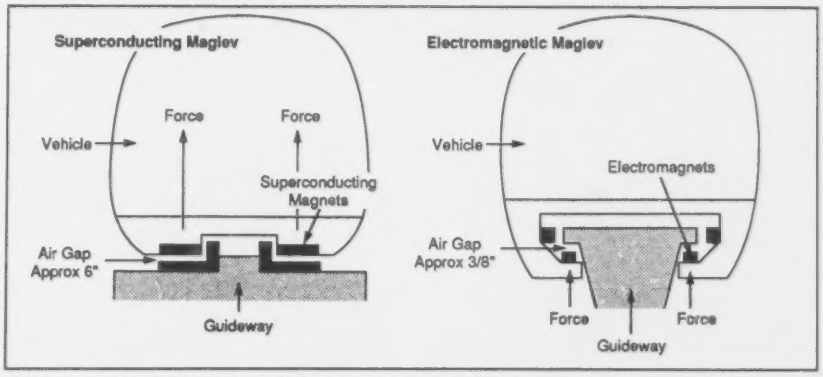
Maglev's potential for high speed, combined with high energy efficiency, greatly enhances mobility; that is, a large volume of people and goods can be economically moved over large distances.

Two kinds of Maglev systems are possible:

- Superconducting Maglev systems have powerful lightweight superconducting magnets mounted on the vehicles. The magnets interact with a guideway of normal metal—usually aluminum—attached to either an on-grade or elevated track structure. Currents are induced in the aluminum only when the vehicle magnets are directly overhead. The guideway is configured to maintain the vehicle in an inherently stable position or "magnetic well." Automatically induced strong restoring forces push the vehicle back to its normal suspended equilibrium position, even if external forces, wind, and guideway curvature try to displace it. Both horizontal and vertical restoring forces can be induced. The typical equilibrium clearance between vehicle and guideway is about 6 inches.
- Electromagnetic Maglev systems have iron core electromagnets along both sides of the vehicle. Electromagnets, located below a pair of laminated steel guide rails attached to the underside of the track structure, are strongly attracted upwards to the guide rails, with an ever increasing force as the gap decreases. The electromagnetic suspension is inherently unstable compared to the inherently stable superconducting suspension and must be actively controlled with servos to prevent the vehicle from contacting the track. Position sensors monitor the vertical gap and quickly instruct power supplies to increase or decrease the current in the copper windings of the electromagnets. To keep vehicle weight and power cost practical, small clearances, typically 3/8 inch, are required between the moving vehicle and the rails on the guideway.

Maglev vehicles lend themselves naturally to electric propulsion using linear motor windings in the guideway. Noise and pollution are greatly reduced compared to generating power onboard. Maglev power is taken from the electric grid, which can come from coal, nuclear, hydro, or solar sources rather than from petroleum fuels.

With such linear motor propulsion for Maglev vehicles, very high energy efficiency is possible as well as inherent safety because of automatic, phase-locked control of location of all vehicles on the track.



Of the two possible Maglev systems, MTAC favors the superconducting approach.

U.S. TRANSPORTATION — PAST SUCCESSES AND PRESENT PROBLEMS

U.S. development initially spread westward, exploiting the ocean waterways as well as rivers and lakes for transport. Man-made waterways such as the Erie Canal were very important in accelerating growth. New communities grew up along the transport pathways, enhancing commerce and resulting in a higher standard of living and greater economic power.

The development of railroads had even greater impact. Locations were not limited by accidents of natural terrain. The country quickly opened up, leading to new sources of natural resources, new industry, and new settlements. Great wealth followed from the economic opportunities and large scale migration of populations across the continent.

The automobile and the truck brought the revolution another step forward. Speeds comparable to railways could be achieved, but with much more flexible and individualistic capabilities. The Interstate highway system, connected to an enormous road network, gave impetus to U.S. industrial and social growth and major improvement in living standards.

The great success of highway and airway travel is creating new problems ...traffic congestion, inefficiency, tremendous energy consumption.

Development of aircraft and the airline industry in the past few decades has been the most recent transport revolution. Like the previous revolutions, it has had a major impact on growth and development. In fact, U.S. preeminence in this field has made us international aviation leaders to this day. Aircraft is the leading sector in U.S. high technology exports, accounting for a trade surplus of more than $10 billion per year.

Aircraft are vitally important to national well-being because of their unique capabilities. However, on a purely volume basis, they comprise only 10% of U.S. transport; highways, waterways, and railroads still carry the bulk of passengers and goods.

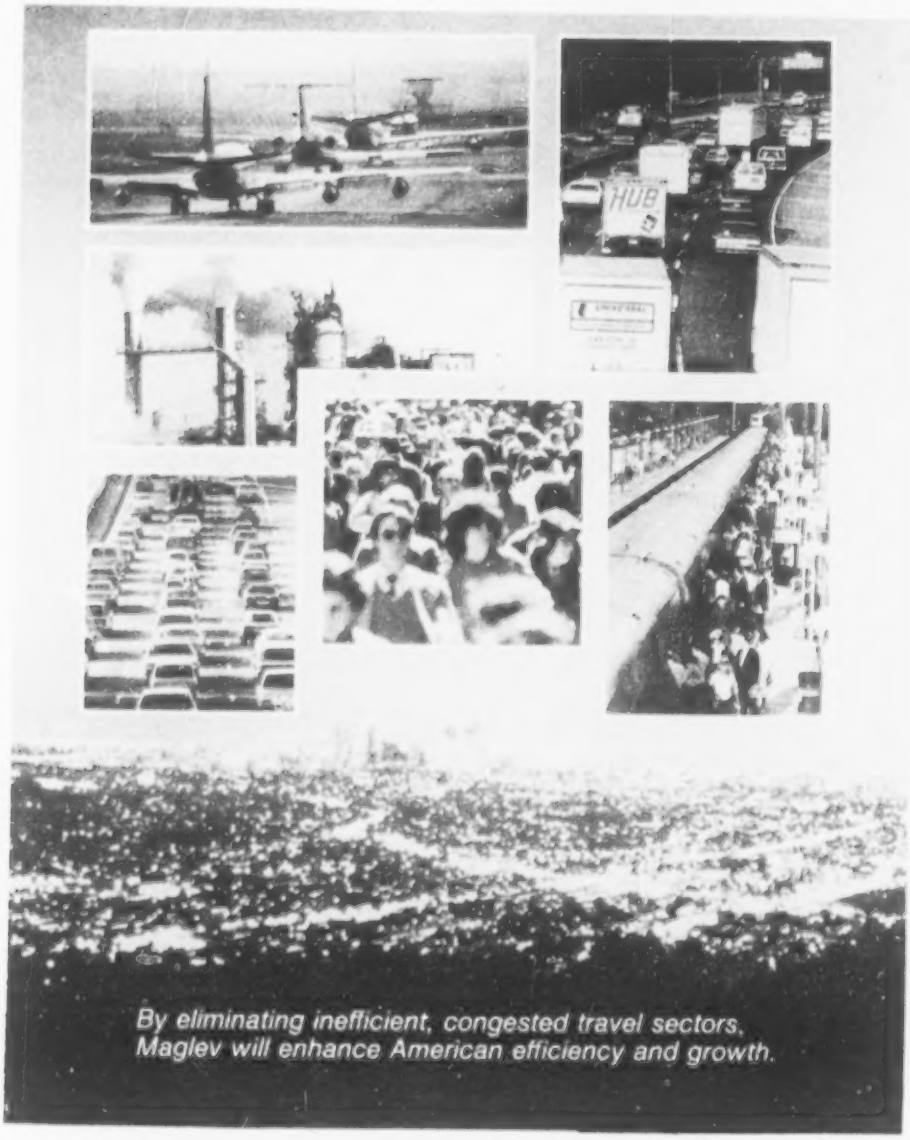
The great success of highway and airway travel is creating new problems. Growth has led to increasing traffic congestion, inefficiency, tremendous energy consumption, and deterioration in many urban and suburban areas. The ability to expand existing transport networks is limited, and costs are increasing enormously. No new airports have been built since 1974. The Interstate highway system is essentially complete, with no major additions planned. The bulk of U.S. population and economic base is located in increasingly congested urban and suburban areas.

A two-way Maglev requiring only 50 feet of right of way can carry the volume of approximately ten lanes of full speed highway traffic.

For large volume transport, Maglev is much less space consuming, costly, and polluting than additional roads. Its inherent high speed—4 to 5 times greater than that of cars and trucks—and its higher energy efficiency plus all-weather capability add up to a unique breakthrough in mobility. Maglev permits decentralization over large areas without isolation. For the same travel time as autos, Maglev can serve a region 25 times larger in area.

What is the alternative? To greatly increase capacity by existing means of transport results in escalating cost. Moreover, the enormous land requirements would cause considerable social dislocation, which is increasingly opposed by the public.

Greater speed has enormous benefit for land use. For example, a two-way Maglev requiring only 50 feet of right of way can carry the volume of approximately 10 lanes of full speed highway traffic. Furthermore, this can be accomplished on existing rights of way. Building additional highways to handle such a volume of traffic would require new rights of way hundreds of feet wide.



By eliminating inefficient, congested travel sectors, Maglev will enhance American efficiency and growth.

Practical Maglev development began first in the U.S.—in the 1960s and early 1970s. The Japanese and Germans started later but continued on while the U.S. dropped out. At that time the great success of the new Interstate highway system was apparent in improving U.S. standards of living and industrial efficiency. Now, however, more and more people realize that there are practical limits.

Second-generation, economical Maglev designs suited to U.S. needs will be the next transport revolution. As in previous revolutions, the new Maglev system will not eliminate the older systems—highways, railroads, and aircraft—but will coexist with them.

Autos will remain vital to many aspects of personal mobility. Local and long distance freight movement will still involve trucks. In many regions, trucks will interact with Maglev systems, receiving and delivering containerized freight to them. Aircraft will remain vital to our economy and to personal travel. By eliminating the inefficient, congested travel sectors, however, Maglev will enhance American efficiency and growth.

IMPORTANCE OF MAGLEV TO THE UNITED STATES

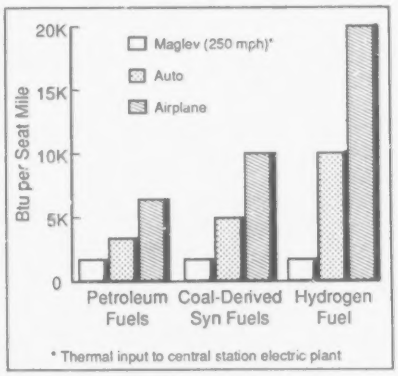
Implementing Maglev in the United States will yield major benefits, including:

- ☐ Improved energy efficiency and security
- ☐ Reduced air pollution
- ☐ Enhanced mobility
- ☐ Lower transportation costs
- ☐ Longer lifetime and reduced maintenance for transport vehicles and infrastructure
- ☐ Greater economic productivity and competitiveness.

Improved Energy Efficiency and Security

Maglev substitutes central station electric power for petroleum-based fuels and requires considerably less energy per passenger mile than autos and airplanes. The U.S. is now importing half its petroleum, at a cost of approximately $50 billion per year, and this fraction will increase with time. Twenty years from now we will be importing approximately 75% of the petroleum we use.

Forty percent of our primary energy is presently supplied by petroleum. Sixty percent of that goes to the transportation sector, almost all of which is fueled by petroleum. The U.S. cannot risk having its transport system completely vulnerable to import cutoffs. Even if imports were completely assured far into the future—improbable in light of the uncertainties that abound in the world—the real price of petroleum would rise dramatically as world reserves are exhausted. We cannot count on cheap, abundant oil in the 21st century. By using central station electric power that comes from coal, nuclear, and hydro plants, Maglev will increase our energy security.



In any fuel economy, Maglev requires less energy than automobiles or airplanes.

Maglev is much more efficient than autos and airplanes. In a petroleum-based transport economy, it is twice as efficient as autos and four times as efficient as airplanes, in terms of gross energy used. Maglev's energy

advantage becomes even greater when it is compared to autos and airplanes powered by synthetic fuels. Typically, the thermal value of synthetic fuels is only about 60% of input energy, if they are derived from fossil (e.g., coal) sources. In the early 21st century, Maglev's competition will be synthetic not natural fuels. The Maglev advantage then becomes a factor of 3 over autos and a factor of 6 over airplanes.

If we consider the long term, when pure hydrogen is favored as a transport fuel to minimize greenhouse effects, Maglev's advantage becomes even more striking. With inexhaustible energy resources (fission, fusion, solar, and hydro) as the prime inputs, Maglev has an energy advantage of 6 over autos and 12 over airplanes.

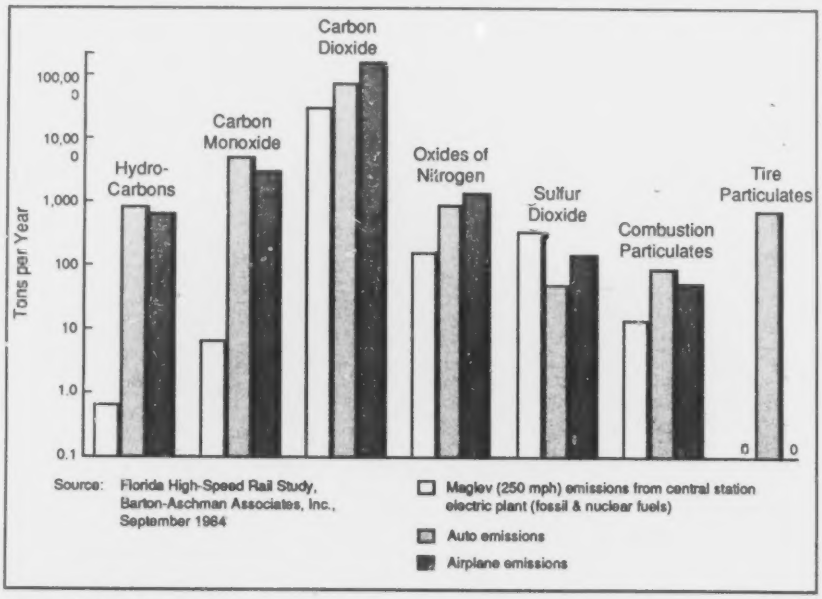
Maglev's energy performance becomes even more attractive if carbon or energy usage taxes are implemented, as has been proposed. In addition, reject heat from power plants can be used for district heating and greenhouses, as is done in a number of European cities.

Reduced Air Pollution

Hand in hand with better energy efficiency are Maglev benefits in reducing air pollution. Electrically powered vehicles do not emit any pollutants, nor does the guideway. In contrast, autos, trucks, and airplanes emit copious quantities of hydrocarbons, carbon monoxide, carbon dioxide, particulates, oxides of nitrogen, and sulfur dioxide.

To a small degree, Maglev operation does produce some pollution, since power plants do emit pollutants. However, these are much less than equivalent auto, truck, and airplane emissions. Moveover, they are usually emitted in rural areas, where pollution is much less of a problem.

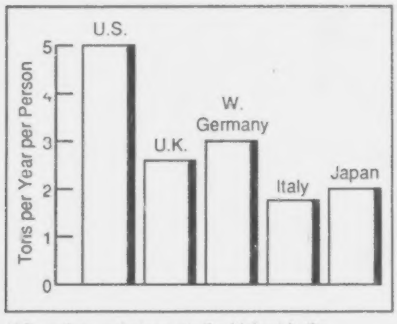
The quantitative reductions possible with Maglev compared to autos and airplanes are illustrated below.



Maglev introduces far fewer pollutants into the environment than automobiles or airplanes (data normalized to 6 million passenger trips per year per transport mode – 800 million passenger miles).

Sulfur dioxide (SO_2) emissions are greater for the Maglev transport mode due to the high sulfur content of coal. However, improved coal cleaning and sulfur control technology should bring SO_2 emissions down. As future electrical generating systems shift toward non-fossil energy sources, reductions in pollution using Maglev will be even greater. However, even with present electric generation plants, Maglev is a factor of 13 less polluting than autos, based on total emissions other than carbon dioxide (CO_2).

Global warming caused by CO_2 emissions is a major concern. The United States discharges much more CO_2 into the atmosphere per capita than any other country in the world, including those with similar living standards and industrial capability, as indicated below. If a significant dent in the problem is to be made, the U.S. will have to show that it can achieve major reductions in CO_2 emissions. This will be extremely difficult for a transport system dependent on petroleum or synthetic fuels, particularly since passenger and truck mileage will increase substantially in the coming decades. Maglev offers a route to greatly reduce CO_2 emissions, even with present electric plants. As we shift to non-fossil fuel sources for electricity, the Maglev potential for CO_2 reduction will become even greater.



U.S. carbon emissions are the highest in the industrial world.

Enhanced Mobility

Maglev will greatly enhance U.S. mobility. The Interstate highway system now carries 22% of U.S. auto and truck traffic, but in many sections it is saturated or near saturation. If we project traffic growth for the next two decades, based on the average growth rate in the past decade, urban Interstates will have to carry three times as much traffic, and rural Interstates twice as much. In many locations, such growth is simply not possible. Instead of stop and go, it will be just stop.

Not only would Maglev relieve congestion, it would dramatically reduce travel time, further enhancing mobility.

With this kind of growth congestion, the Federal Highway Administration estimates that vehicle delays will increase 400% by the year 2005, and city congestion 8% per year. A similar pattern is found for air travel. The FAA estimates that airline delays, which cost us $5 billion in 1986, will increase by a factor of 2 by 1996—only seven years away.

A double-track Maglev guideway located along an Interstate highway right of way can easily carry a hundred thousand passengers per day, and hundreds of loads of containerized freight at off times. Installation of Maglev capacity does not affect or reduce existing auto and truck capability of the Interstates—it adds to it. The carrier potential of Maglev is immense. Current total yearly traffic load on all U.S. highways is 1.3 trillion automobile miles and 500 billion truck miles. A large fraction of this load could be carried by a Maglev network linking U.S. economic and population centers along existing Interstates.

Not only would transport by the Maglev network relieve congestion, it would dramatically reduce travel time, further enhancing mobility. Travel time on Maglev would be a factor of 5 faster than highway trips—even assuming open highway speeds—so that a five-hour journey could be cut to one hour. In addition, Maglev could effectively compete with short-haul aircraft for trips of several hundred miles. Going by Maglev could even be faster than by air, taking into account the time required to reach the airport and the frequent delays caused by air traffic and weather conditions. Maglev will be virtually weather independent, with no delays.

12

Lower Transportation Costs

The cost of Maglev transport should be considerably less than auto and air transport. Currently, air travel costs about 11¢ per passenger mile on a nationwide average. Short-haul air travel costs are substantially higher—in the range of 20¢ to 50¢ per passenger mile. Auto travel averages approximately 33¢ per vehicle mile, including fixed costs (e.g., depreciation and insurance) and variable costs (e.g., gas, maintenance, and tires). Taking the average intercity occupancy rate of autos as 1.9, the equivalent cost for auto travel is 17¢ per passenger mile.

Two facts should be noted about these auto and air travel costs:

- First, they are less than the true cost, since we are allowing the existing infrastructure (e.g., roads and bridges) to decay and the existing vehicle stock to age (e.g., the average life of airplanes is increasing). If we really were at steady state, actual travel would be significantly more expensive, reflecting these hidden costs.
- Second, the cost per mile for auto and air travel is almost independent of the total passenger miles traveled. If U.S. travel doubles in the next decade, it will cost almost twice as much (in 1989 dollars) as it presently does—$1200 billion/year instead of $600 billion. This fact is not generally recognized. As car owners, we understand that if we drive twice as much, we must spend twice as much for gas, oil, tires, and maintenance, but we tend to regard other expenses as fixed. However, they really are not. Driving twice as much depreciates autos twice as fast. Insurance costs will at least double and, more than likely, increase further. (The frequency of collisions tends to go as the square of traffic density.) Only finance charges remain fixed.

Maglev transport costs per passenger mile, on the other hand, will decrease with increasing passenger and cargo use. Most of Maglev's cost is associated with capital intensive components—guideway, right of way (where required), stations, and power equipment—which are independent of the number of passengers carried.

The portions of Maglev transport cost dependent on traffic loading include vehicle capital and operating cost. Generally, the capital cost of vehicles is small compared to the cost of the guideway. Operating costs include energy requirements, personnel, and maintenance and are small compared to fixed charges

Maglev transport costs per passenger mile will decrease with increasing passenger and cargo use.

Passenger transport costs tend to decrease inversely with increasing ridership. However, as ridership becomes very high—50,000 passengers per day and greater—the cost per passenger mile tends to approach a constant value as loading dependent costs become dominant.

Longer Lifetime, Reduced Maintenance

Maglev systems can carry extremely large passenger loadings. Furthermore, they experience very little degradation or wear. The lifetime of Maglev guideways should be extremely long, much longer than roadways or rail lines. Guideway loadings are very low and distributed along the length of the vehicle. There will not be the localized pounding now experienced on highways and rail lines. The Japanese National Railway (JNR) Maglev test track, for example, has not required maintenance since it was built over a decade ago.

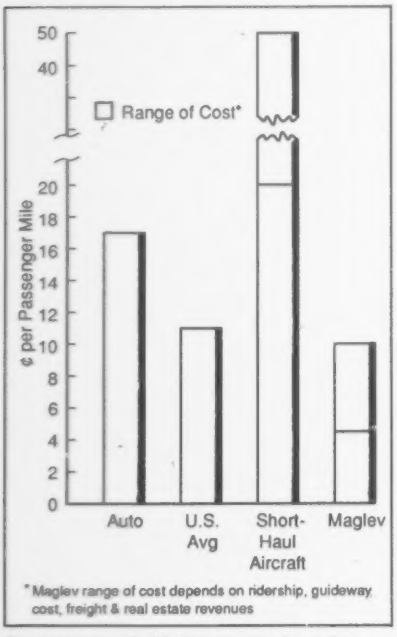
Greater Economic Productivity and Competitiveness

Non-passenger sources of revenue can help to offset the cost of the Maglev guideway, which in turn will reduce passenger transport cost. One important potential source of revenue is from freight transport carried in off-peak periods.

Another important source of revenue that can help defray Maglev guideway investment and reduce passenger travel cost is real estate development. The land around Maglev stations will be extremely valuable for offices,

shopping centers, high-tech parks, and other uses. Grants of land that yield major real estate returns can be a powerful incentive for private investors to help pay for Maglev systems.

The cost per passenger mile for Maglev transport will thus depend on many factors, including ridership, guideway cost, freight revenues, and real estate returns. The comparison of potential Maglev costs per passenger mile with airplane and auto costs shows Maglev costs in the range of 5¢ to 10¢ per passenger mile. The upper end of the range corresponds to a ridership of 30,000 passengers per day and a guideway investment of $10 million per mile; vehicle costs of $4 million per unit; 250 miles per hour operation; and 10¢ per kilowatt hour power costs. A factor of 2 reduction in Maglev passenger costs appears available with higher ridership levels—50,000 passengers per day—and some freight and real estate development.



Per passenger mile, Maglev costs are lower than automobile or airplane costs.

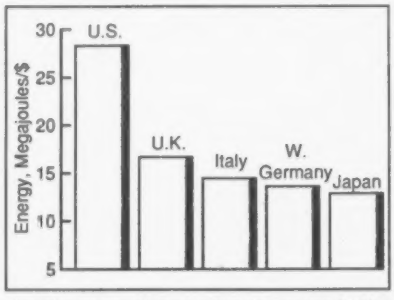
Large-scale implementation of Maglev in the United States will lead to major savings in our national transport bill. We presently spend $600 billion per year in auto, truck, and air transport. This expenditure will grow substantially in future years, even when expressed in constant 1989 dollars, because our economy and population will expand, and petroleum fuels will become scarcer. Savings of many billions of dollars per year appears possible if Maglev is implemented.

Maglev can significantly improve our economic productivity and competitiveness. U.S. economic productivity is held back by a number of factors, including:

- ☐ High transport costs
- ☐ Excessive energy usage
- ☐ Delays and time losses.

The potential direct savings of many billions in direct transport costs if Maglev is implemented would greatly improve national productivity. Moreover, energy usage in the U.S. per dollar of gross national product (GNP) is very high compared with other industrialized nations, as indicated below. Dramatic reductions in energy usage per unit of GNP would greatly help U.S. efficiency and competitiveness. Maglev offers the potential for large-scale energy reductions, particularly of increasingly scarce petroleum fuels.

The effects of delays and time losses on productivity are hard to quantify, but they are real and important. Business travelers lose many working hours through transport delays on airplanes and highways. These are direct losses in productivity. Indirect produc-



The U.S. uses much more energy to produce $1 of GNP than other industrial nations.

tivity losses are even more significant. Congestion and longer distances are increasing the time to get to work. Commuting for hours in traffic takes its toll at the workplace—people are not as efficient, more likely to make mistakes, and less innovative. Increases in productivity resulting from reduced delays will produce major benefits for the U.S.

Maglev systems will be an industry with export potential of billions of dollars per year…The issue is not can we afford to implement Maglev but rather, can we afford not to?

In the last decade, the United States has become less and less competitive in the world manufacturing arena. The chart shows how we fare in various trade sectors. We have a significant surplus ($11 billion per year) in the aircraft and transport equipment sector. In virtually every other manufacturing sector, we either run major trade deficits or barely hold our own. With Maglev helping to increase productivity, U.S. manufacturing competitiveness will improve. Moreover, the manufacture of Maglev systems will be an industry in its own right, with an export potential of billions of dollars per year.

In summary, Maglev offers the United States major economic, environmental, social, and competitiveness benefits. The question is not "Can we afford to implement Maglev?" but rather, "Can we afford not to?"

Product	+	-
Aircraft & Other Transport Equipment	10.8	
Professional, Scientific & Control Instruments	3.0	
Synthetic Resins, Rubbers & Plastics	2.4	
Medicinals & Pharmaceuticals	1.9	
Office & ADP Machines, Parts	1.4	
Organic Chemicals & Products	1.4	
Metalworking Machinery		1.9
Other Industrial Machinery/Parts		2.8
Fibers & Textiles		3.6
Paper & Paperboard		4.0
Other Metal Products		4.5
Other Electrical Machinery & Parts		5.9
Nonferrous Metals		6.3
Nonmetallic Mineral Products		6.7
Iron & Steel Mill Products		8.4
Miscellaneous Products		11.9
Telecommunications/Sound Equipment		16.2
Motor Vehicles, Parts		51.6

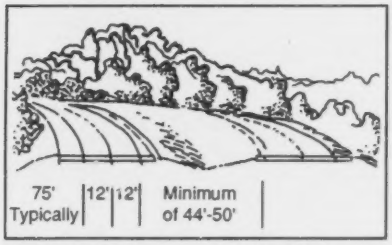
Source: Research & Design, July 1988

American imports and exports (in billions of U.S. dollars) show trade deficits exceeding surpluses by a factor of 6.

MAGLEV AND THE INTERSTATE HIGHWAY SYSTEM

High speed Maglev systems can be built to run beside existing Interstate highways at acceptable cost and without significantly interfering with normal highway operation.

A typical construction for rural Interstates is shown below. The two roadways are separated by a median, which is typically about 50-feet wide. At the side, the distance from the outer edge of the roadway to the right-of-way boundary is usually at least 75 feet. Urban Interstates, which comprise 25% of total Interstate mileage, have significantly narrower medians and side rights of way, and the surrounding area is usually built up.

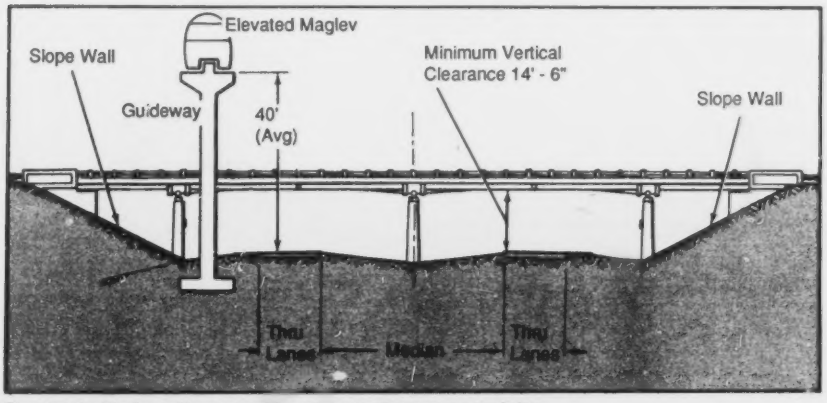


There's ample clearance on rural Interstates for Maglev construction along the median or the right of way.

The physical features of the Interstates—curves, dips and rises, median and side right-of-way widths, bridges and interchanges—constrain Maglev design options, however, and may limit vehicle speed at some locations.

A Maglev guideway will encounter many overpasses and interchanges along its route. Bridges average about one mile apart on rural Interstates, approximately one-half mile on urban Interstates. Most of these bridges are overpasses, where the intersecting highway goes over the Interstate, as illustrated below. Overpasses and ramps constrain Maglev design. Generally, there is not enough room to pass under the bridge at the side, and the guideway would intersect the ramps in any event. Since it is probably not acceptable to relocate or modify most of the bridges and ramps on the Interstates, there are only two options if Maglev systems are to use Interstate rights of way:

- ☐ *Elevate the Maglev guideway to a height of approximately 40 feet, allowing it to pass over existing structures with adequate clearance.* The elevated guideway could either run along the side of the Interstate—the most likely alternative—or in the median if it is sufficiently wide.



Elevating the Maglev guideway provides adequate clearance over existing Interstate bridges and other structures.

- *Run the Maglev guideway at grade level in the median, passing under existing bridges.* This is suitable only for those sections of the Interstates where the medians are wide, straight, and level. If the roadway curves at a faster rate than the high speed Maglev can follow, the guideway must leave the median and go over the roadway. Long spans—hundreds of feet—then result because of the shallow angle between the guideway line and the roadway. Rolling terrain also poses problems for on-grade guideways. Extensive cut and fill operations would be required to maintain a level guideway. This option probably is not practical for most portions of the Interstates.

Another option—that of on-grade or moderately elevated guideways that rise to clear bridges, ramps, and other obstructions—does not appear acceptable. The "transition" distance—the length of the guideway that deviates from a straight, flat path to go over an obstacle—depends on vehicle speed.

If the normal height of the guideway is 20 feet above the roadway, for example, the transition distance to go over a typical overpass is 0.6 mile at 225 miles per hour and 0.8 mile at 300 miles per hour, based on a maximum allowable vertical acceleration of 0.10 g. This assumes that the guideway curves only in the vertical plane. Since distances between overpasses average about the same, vehicles would have to go up and down almost continuously, which probably would disturb passengers.

Elevating the guideway to clear bridges and other obstacles allows Maglev to adapt to rolling terrain.

Vertical acceleration effects can be minimized and the transition distance somewhat shortened by simultaneously curving and banking the guideway in a horizontal direction—the equivalent of a chandelle maneuver in an airplane—though right-of-way constraints may limit such maneuvers. In any case, passengers probably will not tolerate changing vehicle direction every few seconds to clear overpasses. For ride acceptability, Maglev guideways should be flat and straight, with relatively infrequent vertical or horizontal accelerations and at a sufficient height to routinely clear bridges and interchanges.

Maglev vehicles can negotiate virtually all grades on U.S. Interstates at normal speed and with acceptable guideway heights.

Elevating the guideway to clear bridges and other obstacles also allows Maglev to adapt to rolling terrain. Pier height can be adjusted to maintain a flat guideway, even though local ground elevation changes. Occasionally, guideways will have to deviate from flatness to meet long up-and-down grades or large hills. Analyses indicate that such obstacles can be traversed without significant reductions in speed and with allowable vertical accelerations. Guideway transition distances are typically less than a mile, and changes in guideway height are reasonable. Maglev vehicles can negotiate virtually all grades on the Interstates at normal speed and with acceptable guideway heights.

Where the median strip is sufficiently straight and wide, guideways can be located on it. For those sections of the Interstates with curves or narrow medians, however, the guideways can be located along the side of the highway. This avoids forcing the guideway to span the roadway (which would be necessary if the guideway were located on the median) when the Interstate curves relatively rapidly. When guideways are at the side, they can leave the right of way without crossing the roadway.

Generally, it appears that vehicles will be able to negotiate most curves on rural Interstates at high speed. The curves are typically gentle, and additional rights of way can be acquired if necessary.

Curves on urban Interstates are more of a problem, since rights of way are usually narrower, the surrounding areas built up, and the curves tighter. Average vehicle speed on urban Interstates will usually be less than on

rural Interstates, probably in the range of 100 to 150 miles per hour. Stations will be relatively close together in urban areas, and it often will not be desirable to accelerate to high speed. With speeds in the range of 100 to 150 miles per hour, vehicles can negotiate most curves without significantly deviating from existing urban rights of way.

Wind effects from moving Maglev vehicles are minor...noise levels are low.

For abrupt angle curves—rare on Interstates, but they do occur—the guideway will depart from the right of way. For a 30-degree sharp inside curve, the guideway will have a maximum deviation of 250 feet from the right of way for a vehicle speed of 225 miles per hour. This deviation occurs at the point where the roadway makes its abrupt turn. The deviation is less before and after the turn. Maximum deviation of the guideway from the right of way is several times greater for outside curves than for inside curves. When possible, guideways should be located on the inside of the sharpest curves. Optimizing guideway placement will be important in planning Maglev routes.

It should be noted that it is not necessary or desirable that Maglev vehicles stop at every station in urban regions, however. By using off-line loading, Maglev vehicles will be able to stop at selected stations and bypass others. This will minimize start/stop accelerations and delays. The short headways between vehicles that is practical with Maglev will allow passengers to board vehicles to take them to their desired station with a minimum of intermediate stops and waiting.

Wind effects from moving Maglev vehicles are minor. At a distance of 50 feet from the centerline of a 300-mile-per-hour Maglev vehicle, the induced wind speed as it passes is only 3 miles per hour. Effects on highway traffic and surrounding structures will be negligible. At 15 feet—the distance between oppositely moving Maglev vehicles on a double track guideway—induced wind speed is only 20 miles per hour, which is much less than vehicle cruising speed.

Noise levels are low. Maglev vehicles carry no power source; they are driven by track current and do not contact the guideway. The only source of noise is aerodynamic effects on the vehicle body. With elevated guideways and a distance of 50 feet to the roadway, vehicle noise level at the highway is only 70 decibels. This is well below normal auto and truck traffic noise.

A guideway design that minimizes field construction is very desirable. Not only does it reduce cost, but it minimizes disruption of highway traffic when guideways are installed. Elevated guideways would be constructed with prefabricated beams and piers. The piers would be installed on poured concrete footings, and the beams with their aluminum conductors then laid on top. After initial installation, the beams would be adjusted to meet flatness and straightness requirements.

The optimum distance between piers is probably in the range of 50 to 100 feet. Prefabricated beams and piers are light enough to be transported by truck to a convenient access point, where they would be unloaded, then carried along the finished portion of the guideway to their installation point. With this technique and multiple access points, many miles of Maglev routes could be built each year with minimal interference to Interstate traffic or environmental disruption. Detailed cost estimates have not yet been made, but rough estimates indicate that a two-way guideway should cost about $11–13 million per mile for components and installation.

Key Maglev goals: to select an approach that will not become obsolete ...to ensure operation under all U.S. weather conditions.

Compatible vehicle and guideway technology should be used on all Interstate Maglev routes. A key goal in developing the Interstate Maglev system is to select an approach that will not become obsolete and will continue to provide superior performance.

A second key goal is to ensure that the Interstate Maglev system can operate under

all U.S. weather conditions, including heavy snowstorms in the northern and central regions. Plowing or heating hundreds of miles of elevated guideways appears difficult. Guideways may have to be self-cleaning and not accumulate snow and ice. It is not clear to what extent winds induced by moving Maglev vehicles can prevent accumulation. They probably can blow powdered snow away, but may not remove densely packed snow and ice.

Safety and protection of the Maglev system is of prime importance. Highway traffic should not generate safety problems for the Maglev system and vice versa. In general, elevating the guideway resolves many potential safety concerns. Access to the guideway will be restricted, minimizing the possibility of objects being deliberately or accidentally placed on it. Barriers can protect the piers from impact with trucks and autos that leave the roadway. Noise and wind effects on highway traffic appear to be negligible. And locating the guideways at the side of the roadway will minimize visual distraction, since most drivers tend to look forward to the highway vanishing point.

Maglev can help bring depressed regions into an integrated national transport system, improving living standards and relieving overcrowding.

The first generation Maglev systems now being tested in Japan and the Federal Republic of Germany are not optimized for application to the U.S. Interstates. Issues for Maglev Interstate systems include compatability with existing bridges and interchanges, field construction requirements, and ability to operate after severe winter storms.

Optimized second-generation Maglev systems can be developed to meet Interstate requirements, with low enough cost so that Maglev can be widely implemented. In our view, second-generation Maglev systems based on superconducting magnets appear more promising than systems based on electromagnets for three reasons:

- Superconducting Maglev vehicles will be lighter, typically 40 tons (gross) compared to 100 tons (gross) for electromagnetic Maglev vehicles. This will result in lighter, lower cost guideways.
- Large clearances between vehicles and the guideway—typically 6 inches for superconducting Maglev vehicles compared to 3/8 inch for electromagnetic Maglev vehicles—will make guideway installation and maintenance easier and cheaper.
- The guideway propulsion system is simpler and cheaper because drive windings for electromagnetic systems have a much smaller pitch and a more complex overlapping design.

We have examined promising Maglev Interstate routes to determine their transport potential. Three types of systems were investigated: metropolitan feeder, intercity linear corridor, and multistate networks.

Metropolitan feeder systems would interconnect distant portions of a metropolitan area and its central core. A Long Island-New York City Maglev system (I-495) was examined in detail. Overall length is about 100 miles, with an average spacing between stations of approximately 15 miles. Operating speed would be 100 to 150 miles per hour. Many U.S. metropolitan regions—Washington, D.C., Los Angeles, and Chicago, for example—could increase mobility using Maglev feeders along the Interstates.

Intercity linear corridors also appear very promising. We examined a San Francisco-Los Angeles-San Diego Maglev system [I-5] and concluded that this corridor, along with side branches [I-10], would serve almost all of the population of California. Other possible linear corridors include Boston-New York-Washington, D.C., Chicago-Detroit, and Dallas-Fort Worth-Houston.

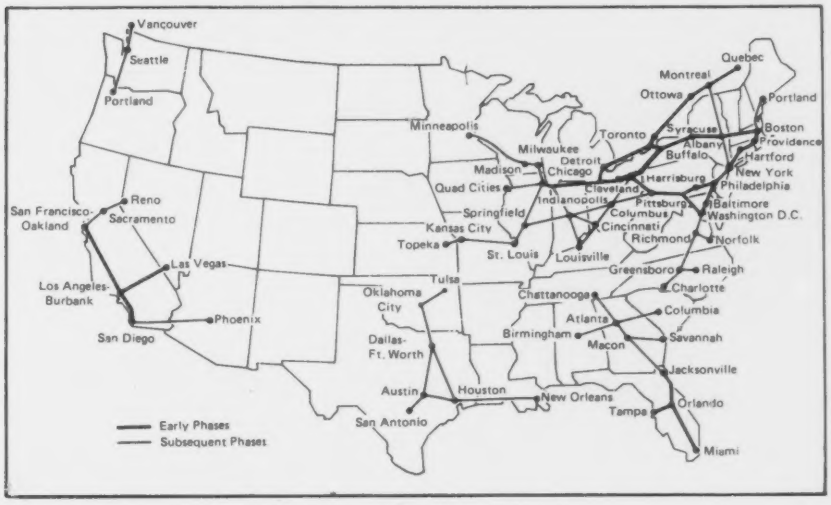
Maximum benefits will result from multistate Maglev system networks. The Interstate highway system has been extremely successful. It interconnects the major U.S. economic centers, with minimum travel time and delay. As in any network, the number of connections increase as n times n, where n is the total number of different nodes. The Interstate highway system would be much less useful if it were just separate linear corridors

between cities, with little or no interconnections. Similarly, Maglev systems will be most useful if they form interconnected networks.

An example of Maglev networks connecting most of the major U.S. economic and population centers is shown below. The Eastern U.S. is served by three networks—Northern, South Central, and Southeast. Additional Maglev links between New Orleans-Birmingham, Tulsa-Kansas City, and Norfolk-Chattanooga would tie the East into one large network. Other links could tie the Western U.S. to the East.

In considering potential routes, it should be kept in mind that Maglev will not only be useful in connecting present population and economic centers, but can enable new and more desirable population distributions. Many regions in the U.S. now suffer economically because they are not served by effective transport. Maglev can help bring depressed regions into an integrated national transport system, improving living standards and relieving overcrowding.

Due to limited time and resources, the Maglev Interstate studies described in this report have been generic in nature, using average highway characteristics. The next step should be to investigate several promising Interstate routes in detail, taking into account actual features: curve type and radius of curvature; nature of terrain; right of way widths; and similar technical questions.



Maglev along existing U.S. Interstate highways would connect economic and population centers in various parts of the country.

U.S. Development

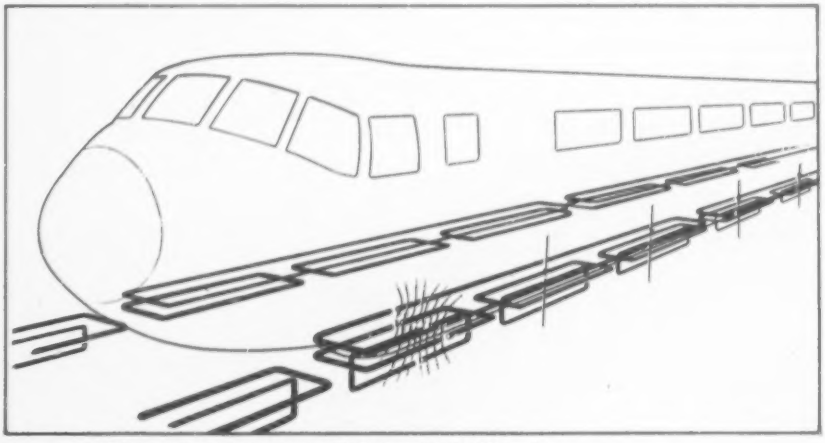
Practical superconducing Maglev was invented and development started in the U.S. in the 1960s. The U.S. pioneered the basic conceptual ideas in superconducting Maglev and dominated the early experimental work. However, by the mid-1970s the U.S. effort had effectively ceased for lack of support to carry it to the next stage.

In 1968 James Powell and Gordon Danby patented the concept illustrated below, which employs superconducting magnets in a vehicle interacting with shorted aluminum loops in the guideway (at ambient temperature) to achieve large clearance suspension. The loops provide strong lifting and restoring forces, both horizontally and vertically. The forces are automatically induced by the (moving) magnets as the vehicle passes by. Typically a 100,000-pound vehicle could be levitated 6 inches and travel up to 300 miles per hour in air.

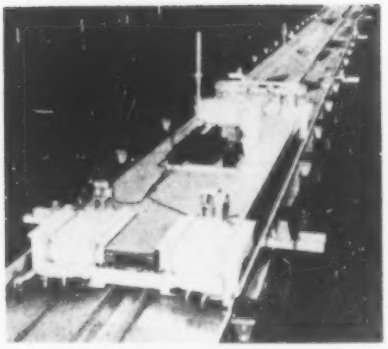
Subsequently they invented systems, called null-flux configurations, that provide strong and efficient levitation forces. They also devised linear synchronous motor concepts for their superconducting vehicle designs. The strong on-board magnets were acted upon by motor windings located on the roadbed to provide efficient, intrinsically stable propulsion and braking. They also described systems in which the superconducting magnets are attracted to iron which, in combination with null flux stabilization loops, permit heavy freight to be very efficiently transported.

In 1967–68, Stanford Research Institute (SRI) and Rockwell International, with the support and collaboration of Sandia Corporation, studied ways to magnetically levitate very high speed rocket sleds. These studies produced the continuous aluminum sheet guideway form of magnetic levitation in contrast to the coils proposed above. Fabrication and installation costs for this type of construction are expected to be lower, while electromagnetic drag and power requirements are higher.

John Reitz and Craig Davis of the Ford Motor Company's Scientific Research Laboratories began studying the continuous sheet model in 1969. Howard Coffey and Frank Chilton of SRI constructed a 500-foot long test guideway in 1970. Both organizations were funded by the Federal Railroad Administration in 1971 to assess the feasibility of magnetically levitating high speed ground vehicles.



As early as 1968, Powell and Danby received U.S. Patent 3,470,828 on this American concept for a superconducting Maglev vehicle and guideway.



Constructed at SRI in 1970, this magnetically levitated vehicle on an aluminum sheet guideway is an example of American Maglev initiative.

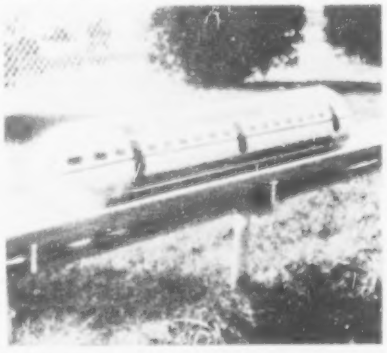
Ford also performed experiments with a superconducting magnet suspended above a rotating aluminum drum, and SRI performed analogous experiments on its guideway. Both groups studied electromagnetic and superconducting forms of Maglev and both preferred the continuous sheet guideway concept. Both groups also developed and verified analytical techniques for calculating the forces experienced by the magnets. This work at SRI and Ford continued through 1974 and 1975.

SRI constructed and magnetically levitated a vehicle weighing 1100 pounds and evaluated its dynamic performance with active and passive damping and various perturbations in the guideway. Ford performed extensive analyses and made many measurements on their rotating drum (which would have been very expensive or difficult to perform on a guideway) and developed a baseline model for a revenue vehicle. Among other topics, magnetic support and guidance, guideway configurations and interactions, active and passive damping, ride quality criteria, cryogenic and superconductive requirements and techniques, power requirements, propulsion techniques, vehicle stability, and guideway imperfection studies were made by one or both groups.

General Motors Corporation instituted a program on magnetic levitation and, at one point, was considering installing a usable system at its research site. They performed studies of linear synchronous propulsion on a rotating wheel apparatus and filed at least one patent application.

Rohr Corporation and Boeing Aerospace Corporation developed two forms of an electromagnetic Maglev system. The rights to this technology were later transferred to Carnegie-Mellon University.

Henry Kolm and Richard Thornton at MIT filed a series of patents* on an integrated superconducting propulsion system known as the MIT Magneplane. The work was supported by MIT, Raytheon, and Avco, with contributions from Alcoa, 3-M, and the National Science Foundation. The MIT Magneplane project involved about 100 students and engineers who constructed three generations of 1/25-scale model systems that operated at 60 miles per hour on a 400-foot-long guideway using superconducting magnets. An active damping system was developed to improve ride quality.



The Magneplane, developed at M.I.T. in the early 1970s, was a 1/25 scale model of a superconducting propulsion system that operated on a 400-foot guideway.

The MIT Magneplane differs from other concepts in several respects. Vehicles are free to roll into a coordinated bank angle in a trough guideway when negotiating curves. The capability of banking in a trough guideway was expected to allow Magneplane vehicles to negotiate tighter curves and grade changes along a right of way. Vehicles are

*U.S. Patents 3,768,417 (1973); 3,842,751 (1974); 2,871,321 (1975); and fourth Magneplane patent pending (1988).

propelled by a synchronous wave, which enables a central computer to maintain headways of only 20 seconds without danger of collision. To load and off-load passengers, vehicles leave the guideway on retractable wheels that engage ramps on the guideway edge leading to overhead stations or sidings.

While the U.S. stopped funding Maglev in 1975, other countries, principally Japan and West Germany, went on to develop very impressive large-scale projects with passenger-carrying demonstration vehicles, supported by their governments and industries.

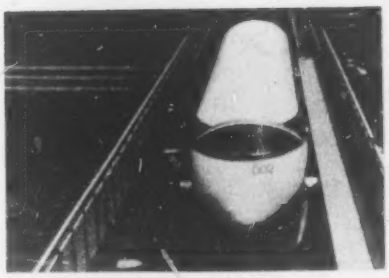
Maglev is now at a critical juncture. Application to actual revenue-producing service systems is being planned in both Japan and West Germany. In the U.S., a number of revenue transport systems that would use this foreign technology are under consideration. Maglev is increasingly recognized as the next revolution in transport.

The U.S. has the capability and industrial know-how to leapfrog to the forefront of this exciting technology. This assumes that a real commitment is made soon to develop systems appropriate to U.S. needs in the next few years.

Japanese Development

In 1970 the Japanese National Railway (JNR) started serious development of superconducting Maglev under the leadership of Y. Kyotani. JNR constructed a 7-kilometer test track in Miyazaki, where they successfully operated a 300-mile-per-hour vehicle a decade ago. The levitation and propulsion systems used by JNR are based on the Powell and Danby concepts described above. The Japanese carried out studies on dynamical stability, damping of oscillations, operational behavior of magnets and refrigerators, and safety. They have conducted detailed research for over a decade. During this time they developed new vehicles and reconfigured guideway geometry. Multiple coupled vehicle combinations, both two and three vehicles, have been successfully operated.

Based on JNR's superconducting Maglev research and development, new Japanese companies are now planning to build the first operational revenue-producing systems at several locations in Japan.



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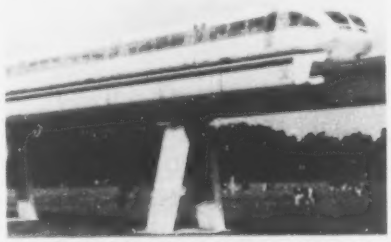
This full size Japanese National Railway superconducting Maglev vehicle was trial tested at 300 miles per hour on a 7-kilometer track

West German Development

The West German Maglev effort started out on a dual track, following both the superconducting and electromagnetic Maglev approaches. About a decade ago, they ceased work on superconducting systems and concentrated on electromagnetic Maglev. This decision was based on the belief that electromagnetic technology was more near-term, since it used iron electromagnets attached to the vehicle with copper or aluminum exciting coils rather than superconducting magnets. These magnets are attracted upwards to two laminated guides on the underside of the guideway. This attractive force is unstable, but the gap clearance (approximately 3/8 inch) is maintained by rapidly adjusting magnet currents up and down.

The German system, called Transrapid, has been tested with vehicles traveling up to 256 miles per hour on a 31.5-kilometer.



Courtesy of Transrapid International

Transrapid, *a full size West German electromagnetic maglev system, has achieved speeds of 256 miles per hour on a 31.5-kilometer test track.*

closed-loop test track at Emsland, Germany is considering building revenue-producing operational systems in the next decade, possibly between Hamburg and Hanover.

It should be noted that a second Japanese system, the HSST, is similar to the Transrapid in that it also uses servoed electromagnets. However, it is considered an intermediate rather than a high speed system. A slow speed (22 miles per hour) people-mover electromagnetic suspension system has been operating for years at the Birmingham airport in England.

U.S. Capability to "Leapfrog" to the Forefront

Electromagnetic Maglev systems have demonstrated successful, safe operational capability and undoubtedly will be built in the U.S. as well as in their home countries. However, we believe that the superconducting Maglev approach is much more promising for U.S. Maglev systems. The large track-vehicle clearances, lightweight vehicle construction, potentially cheaper guideways, and, ultimately, freight potential of superconducting Maglev appear superior for U.S. needs.

Most of the early Maglev pioneering took place in the U.S. The individuals involved remain interested and informed in Maglev. Many others with relevant technical expertise will be eager to join in a serious program.

The lightweight vehicles required closely resemble aircraft structure. The U.S. aerospace industry is the best in the world and eminently capable of quickly taking on levitated vehicle construction.

The major part of the development of superconductors, cryogenics, and refrigerators has been carried out by U.S. companies. This industrial expertise still exists. For 20 years superconducting devices have been successfully built and operated in the U.S. on a scale greater than in any other country. The bulk of this work has been directed to apparatus for scientific research. U.S. industry has participated heavily in this field and can be immediately mobilized for Maglev cryogenic systems.

Maglev magnets are quite simple compared to many other successful superconducting magnets. The commercial application of superconductors has awaited products with large-scale market application. With volume production it is practical to produce small refrigerators for operation in the field. Mobile, closed-loop refrigerators are commercially available. They can maintain 15 tons of superconducting magnets at liquid helium temperature and weigh only one ton.

Magnetic Resonance Imaging diagnostic medical scanning is the first such application. More than a thousand large superconducting scanner magnets are in successful, safe, and reliable operation in clinics and hospitals, requiring minimal expert maintenance, and the number is rapidly increasing. Maglev will be an even bigger market for superconducting magnets.

A new element in the discussion of Maglev is the recent discovery of high temperature superconductors. These superconductors are expected to have a large impact on electronics in the future. They may also eventually have a major impact on high power electromagnetic devices, such as those used in Maglev.

The availability of these new high temperature superconductors does not affect the feasibility of superconducting Maglev systems. Present superconducting magnets and helium refrigerators are adequate and represent only a small fraction of vehicle cost. The vehicles, in turn, represent a small fraction of total system costs, which are dominated by the guideway. The economics of superconductors then is not an issue that determines Maglev practicality. High temperature superconductors will have only a small impact on costs. They could simplify operation but are not required for implementation.

When high-temperature superconductors become available, they will be welcome. The magnet system could be made cheaper and simpler at higher temperatures.

To illustrate that present low temperature superconductors are economically practical for Maglev, consider the Superconducting Super Collider (SSC). The total length of magnets planned for the SSC is 100 kilometers, which corresponds to magnets for 3000 Maglev vehicles. These 3000 vehicles could carry 20% of total U.S. annual passenger miles. The SSC magnets, which are much more difficult technically than those for Maglev vehicles, will cost approximately $1 billion,

equivalent to a unit cost of $300 thousand per Maglev vehicle. This contributes less than 0.1¢ per passenger mile to Maglev transport cost.

A New U.S. Initiative in Maglev

What about the question of the foreign lead, with the billion dollars spent in Japan and in Germany on Maglev development demonstrations? This experience is a competitive advantage but it can be overestimated.

They are to be commended for their foresight and dedication. However, everyone with the technical capacity to compete benefits greatly from their successful first embodiments. Many of the inevitable objections and questions (Does it work?, Is it safe?) that arise for anything new have been answered. Much money and time have been saved bypassing this preliminary stage in the U.S. Important information can be deduced from the performance of Maglev systems reported in the literature.

The timing for Maglev is strategic... in a few years the opportunity to leapfrog will vanish.

Large-scale demonstration projects require commitment very early to specific, not easily changed design parameters. Invariably, before completion, the builders change their minds on many features and realize how they could be improved. Informed observers can also draw the same conclusions.

New U.S. efforts will start from a world base of knowledge that cost $2 billion and years of effort. The timing is strategic—in a few years the opportunity to leapfrog will vanish.

A very important reason for a major U.S. initiative is that superconducting Maglev can undergo further development. Major advances will occur as a result of future efforts. Some say the U.S. is "behind" and should just "buy foreign." This is foolishly shortsighted. Such philosophy is not followed by our foreign competitors.

Transport is a huge industry. It is too basic to the U.S. economy and national well being not to be a prime mover in our technical development. Let us create jobs and benefit from exports to others rather than the other way around. Building under license produces only a fraction of the benefits.

Rather than wait for other countries to develop second generation systems, the U.S. should push ahead with its own program.

Finally, U.S. transportation needs are quite different from those of Japan or Europe. Consequently their transportation systems have developed quite differently from ours.

Japan is very crowded and very mountainous. Design choices of transport systems are strongly influenced by questions of tunneling and coping with extreme urban congestion. This has a major impact on roadbed, guideway, and vehicle design choices. System costs are dominated by this series of choices.

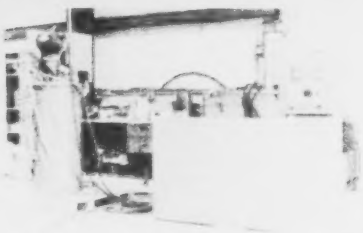
Europe's geographic and demographic situation is in many ways more similar to Japan's than to the U.S. The U.S., on the other hand, requires large-scale, low cost systems appropriate to our great distances and less severe terrain.

Our enormous resource, the large Interstate highway network, offers the possibility of thousands of miles of virtually free rights of way. This has a dominating impact on system choices. Guideways and support structures must be compatible with the Interstates for very large-scale, economical deployment.

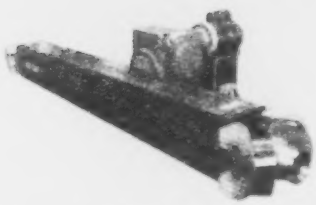
For the longer term, freight must be considered. Moving goods quickly and efficiently is also very important if Maglev is to truly complement existing modes of transportation. The system finally chosen for large-scale U.S. deployment should have guideways that are compatible with both light passenger vehicles and vehicles carrying freight loads.

The heart of the MRI whole body scanner is a massive cylindrical superconducting magnet that generates the high field strengths needed to produce soft tissue images.

The superconducting magnet for the Tevatron is housed in the lower ring of the accelerator tunnel at Fermilab.



The Koch helium liquifier/refrigerator being tested here is designed specifically for maintaining superconducting magnets at cryogenic temperatures.



This superconducting magnet for the alternating gradient synchrotron at Brookhaven National Laboratory has approximately the field strength needed for Maglev.

These large General Dynamics magnets are examples of products manufactured by U.S. companies for superconductivity research.

American expertise and experience in superconductors and cryogenics can quickly be mobilized to implement Maglev.

IMPLEMENTING MAGLEV IN THE UNITED STATES

In our view, it is not a question of whether or not Maglev will be implemented in the United States. It will be. The real issues are:

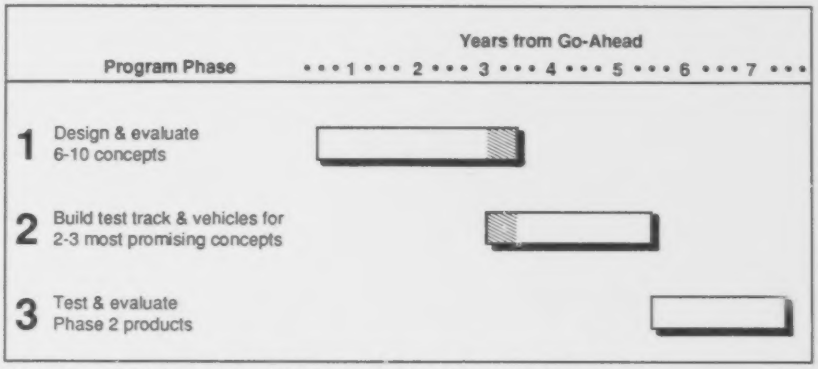
- ☐ Will Maglev systems be optimized for American conditions?
- ☐ Will American industry develop and manufacture Maglev, or will we buy foreign systems?

To be integrated with the Interstate highway system, second generation Maglev technology should be developed. This technology will enable large-scale implementation, with major economic, environmental, social, and industrial benefits.

Rather than wait for other countries to develop second generation systems and then buy their technology, the U.S. should push ahead with its own program. The costs of Maglev development will be much smaller than the economic benefits it will bring, much smaller than buying foreign systems, and much smaller than the value of exports to be gained by selling our technology to other countries.

It should be noted that the Japanese and German Maglev developments have been funded by their governments. If the U.S. is to compete, it will require strong governmental support for Maglev development and demonstration. A U.S. Maglev program will need:

- ☐ Development and demonstration of second generation, high performance, low cost Maglev systems suitable for installation along the Interstates
- ☐ Long-term commitments with clear goals and success criteria
- ☐ Fast-track, skilled management
- ☐ Passage of legislation setting up administrative and regulatory entities to initiate, build, and operate commercial Maglev systems
- ☐ Establishment of funding sources to finance the construction of Maglev routes.
- ☐ Patents and technology protection.


Years from Go-Ahead
Program Phase
1 2 3 4 5 6 7
1 Design & evaluate 6-10 concepts
2 Build test track & vehicles for 2-3 most promising concepts
3 Test & evaluate Phase 2 products

Within 7 years, the U.S. can design, build, test, and evaluate the optimum Maglev system for implementation along existing Interstate highways.

Development and Demonstration

There is a variety of possible design concepts for a second generation Maglev system. However, these need to be developed in detail, and it appears premature to fix on one approach. A competitive "horse-race" type of development program is desirable, in which proposed concepts—six or more—are analyzed and critically evaluated. Important technical questions should also be subject to experimental tests in this first phase of development.

At the end of this Phase 1 activity, lasting two or three years, the best concepts—two or three at most—would be selected for Phase 2 development. In Phase 2, a 20- to 30-mile closed-loop test track would be built for the selected concepts. Full size vehicles would be realistically tested under conditions (acceleration, deceleration, speed, curves, terrain, weather, etc) that duplicate those expected for commercial Maglev systems. Design and construction of these demonstration tracks would take approximately two years. At the end of this period the third and final phase of actually testing and evaluation of alternate concepts would begin.

We feel it is not appropriate to select design approaches for Phase 1 development in this report. There will be a wide variety of proposals forthcoming, both from groups with previous Maglev experience and from new sources. It would be counterproductive at this time to try to predict which will ultimately be the best. Although we strongly believe that superconducting Maglev is the most promising approach for lightweight, high performance, second generation systems for the Interstates, we do not rule out electromagnetic Maglev, which could also be proposed.

The development program should be industry oriented in both Phase 1 and Phase 2. Maglev is no longer a research effort. It has been shown to be feasible and practical. Achieving a second generation system involves high tech engineering to improve and integrate existing components—magnets, refrigerators, structures, aerodynamic bodies, etc—whose technology is well understood. The "lessons learned" with the successful JNR and Transrapid Maglev systems will provide a valuable base on which to build second generation technology. However, research can make valuable contributions in particular areas, such as high temperature superconductors, drag reduction through boundary layer control, etc. Breakthroughs in such areas, while not necessary to the success of second generation Maglev systems, could substantially improve their performance. In addition, the analytical and experimental capabilities available in U.S. universities and national laboratories can make valuable contributions to the development program. This can be done through the formation of integrated consortia with industrial, university, and national laboratory partners.

Total government funding for Phase 1 is estimated to be about $100 million (1989 dollars). This would cover studies of approximately six concepts in Phase 1, down-selected to two concepts in Phase 2. The Phase 2 program would cover construction and startup of two demonstration test tracks, with an estimated cost of $500 million. Additional funding will be required if three concepts are selected for Phase 2. Phases 1 and 2 would take a total of four to five years. In Phase 3—testing—performance, reliability, and safety tests would be carried out using the demonstration tracks, along with engineering design studies of commercial Maglev systems. These activities will enable selection of the best Maglev concept for commercial implementation. Approximately $150 million (1989 dollars) and two more years would be required for Phase 3. Safety certification costs are not included. It may be possible to incorporate one or both of the test tracks into later commercial systems.

Long-Term Commitment

To meet program schedules and objectives, there must be a long-term commitment and assured funding. Interruptions in funding and stretchouts will seriously compromise the program.

The Maglev development program must have a clear set of goals and success criteria to judge performance. Areas to be evaluated include vehicle operational capabilities (speed, noise emissions, drive power, passenger capacity, weight, etc); adaptability to the Interstates (curve capability, grade capability, visibility, installation effects, etc); costs (guideway, vehicles, operating, and

maintenance); and safety. Studies of Maglev application to various Interstate routes will provide a detailed data base that can be used to set goals and success criteria. These studies should be carried out early in Phase 1. Analyses of financial feasibility and projected ridership and freight revenue levels will be important ingredients, and involving appropriate state agencies is vital.

Fast-Track, Skilled Management

Fast track, skilled management is also vital. There presently is no federal agency with expertise in Maglev or even in the general field of high-speed ground transport. Aggressive, highly competent management is a critical requirement, both in the near term for technology development and in the longer term for commercial implementation.

A basic requirement for Maglev implementation is passage of enabling legislation—both federal and state.

Establishing an effective federal administrative structure for Maglev will take time. To catch up in Maglev, a quick-start program is needed. The best way to do this is to use existing management resources to develop Maglev technology through Phase 3.

Various kinds of management structures have been used for U.S. high technology projects over the years. We have considered possible approaches and recommend that an existing government agency be selected to manage Maglev development. The agency should have a fast-track, mission-oriented outlook. The goal should be to demonstrate second generation Maglev technology suitable for commercial systems in six to seven years.

The agency should not carry out Maglev development in-house. Industry should be involved from the beginning, in partnership with universities and national laboratories where appropriate. This will minimize the time needed for commercial implementation.

Passage of Legislation

The next basic requirement for Maglev implementation is the passage of enabling legislation. Both federal and state level legislation is needed to allow Maglev systems to use the Interstate rights of way, to resolve zoning conflicts, to set procedures for environmental permits, to acquire needed land by purchase or eminent domain, to grant franchises for real estate development, and so on. Potential problems and conflicts will have to be resolved before private investors and/or government—both federal and state—can proceed to build Maglev systems. Safety procedures, certification, and liability responsibility will also have to be addressed.

Program Funding

Availability of funding is another basic requirement for implementing Maglev. Capital cost will be dominated by the guideway, followed by the stations and power equipment. Capital cost for vehicles is a small portion of the total. Investment is thus heavily front-end loaded before revenues start to flow.

Over the next ten years, with our present transport system, the U.S. transport bill will be at least $12.000 billion (constant 1989 dollars), and probably considerably more due to increasing demand and fuel cost. Large-scale implementation of Maglev could save a significant portion of this expenditure.

In this context, the cost of U.S. Maglev development—approximately three quarters of a billion dollars—is small compared to the benefits it will bring. Moreover, the capital investment in Maglev systems will also be small compared to our total transport bill.

Maglev systems can be self-financing...with enough left over to pay back capital investment over a period of years.

Money to construct Maglev systems can come from both public and private sectors. Private financing could come from the sale of franchises for real estate development related to Maglev systems.

Implementation of Maglev will be affected by the capital cost of Maglev systems, the amount of their revenues, and the availabil-

ity of investment funds. Rough estimates indicate that Maglev capital cost will be approximately $10 million per mile of two-way guideway. With passenger, freight, and real estate development revenues, Maglev systems can be self-financing—that is, revenues will cover operating costs, with enough left over to pay back capital investment over a period of years.

Self-financing systems are very desirable, since the return of capital investment allows the construction of new Maglev routes at a more rapid rate than if capital is not returned.

Patents and Technology Protection

Finally, there are the critical issues of patents and technology protection. The U.S. has fallen behind in the Maglev race, and reestablishing an effective program will take time. However, our foreign competitors will not be standing still during this period, and their commitments are much greater.

The race for second generation Maglev systems will be decided within the next few years, and will turn on who obtains the patents on the new technology. The original U.S. basic Maglev patents have either expired or will expire in a few years. In a relatively short time, all of the viable second generation derivative Maglev approaches can be conceptually explored and analyzed sufficiently to obtain follow-up patents—the number involved is not large. In effect, there will be a "picket fence" of patents that covers all practical variations on second generation technology.

If this "picket fence" is held by foreign competitors, there will be no U.S. Maglev industry, except as a licensee. Much of the potential competitiveness and trade benefits to the U.S. will be lost, and Maglev systems will be more expensive. Furthermore, development of new, more optimized systems for U.S. conditions may be slowed or stopped, because of differing priorities and investment in already developed foreign technology. Without patent protection, U.S. industry will not put in the resources needed to develop second generation systems.

Allied to patents is the issue of technology protection. Detailed discussion and description of advanced Maglev concepts and technology, without suitable protection, could in effect "give away the store." Indeed this was the case with U.S. Maglev efforts in the 1960s and early 1970s. We believe that the U.S. Maglev program should have strong confidentiality and safeguard provisions built in, and that suitable protection be obtained before important information is publicly released.

CONCLUSIONS AND RECOMMENDATIONS

The Maglev Technology Advisory Committee (MTAC) concludes that Maglev technology offers uniquely attractive solutions for U.S. domestic and worldwide transportation needs and is destined to soon become a significant part of the transportation market. Construction of the next generation transportation system will be a massive, major industrial venture, and it is vital that the U.S. play a major role.

The key Maglev concepts and technologies were invented and pursued successfully in the United States during the 1960s and early 1970s, but our leadership role was relinquished when government support terminated in 1975. Since then, Germany and Japan have each spent about one billion dollars on Maglev technology. A first generation electromagnetic Maglev system is planned for introduction in Florida by 1994, with joint funding by Germany and Japan. We do not consider the present first-generation Maglev technology to be the best long-term choice for the United States. A better second generation system can be developed in a few years with U.S. talents and resources. This opportunity is of limited duration, however.

The financial incentives of Maglev transportation are sufficiently compelling for private industry to assume part of the cost for commercial systems, providing the federal government acts promptly and provides the necessary leadership.

We believe that a significant portion of the funding for the new Maglev transportation systems can be generated by the value the system will create. This approach represents a modern version of the Land Grant Act, which stimulated construction of the railroads in 1830. Florida passed legislation in 1982, incorporating a version of value capture. Their legislation could be a model for federal legislation. While important, however, it should not be viewed as the sole source of funds to defray the cost of commercial systems.

MTAC recommends the following specific actions:

- ☐ Begin immediately an education campaign to explain the issues and options to the public, academia, government, and industry, with assistance from public and private media. This is necessary to generate public interest and political support for prompt action.
- ☐ Adopt the goal of constructing full-scale test and demonstration systems suitable for integration with highways within five years, with the first revenue-producing system to begin operation as soon as possible thereafter.
- ☐ Provide dedicated funding in the amount of $750 million over a period of six to seven years for developing, testing, and demonstrating several prototypes of alternative Maglev technologies that meet U.S. requirements and are suitable for installation along the Interstates.
- ☐ Appoint an agency to manage the project of comparing and downselecting alternative systems and constructing full-scale tracks for the two or three most promising ones. This agency should have strong industry connections, be mission-oriented, and experienced in carrying out large-scale projects.
- ☐ Formulate a national "value capture" policy whereby highway easements and adjacent development rights can be franchised to private consortia to help generate the capital necessary to build Maglev systems.
- ☐ Pass federal legislation and encourage the passage of state enabling legislation, including tax incentives and measures for dealing with problems involving antitrust laws, eminent-domain authority, zoning conflicts, environmental impact, state and local rights, and private development franchises.
- ☐ Establish an administrative structure that will act to implement Maglev systems in the U.S. and establish and enforce quality and safety standards. This structure should come into effect six to seven years after the research and development period.

We consider it vital to the economic, industrial, and environmental well-being of the United States to resume our lost leadership in transportation by acting decisively before the present opportunity is lost.